

OPTIMIZATION OF PULSED CURRENT PROFILE FOR MAGNETIC FIELD TRAPPING IN HIGH T_c SUPERCONDUCTORS

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Abstract

Compared with conventional field-cooling and zero-field cooling magnetization methods, pulsed field magnetization is an alternative way to magnetize high temperature superconductors (HTS) with the advantage of dramatically decreasing the size and complexity of the electromagnetic system. Experiments were carried out with a flexible pulsed-current generator. A series of three pulses was found to be adequate to magnetize the HTS monolith with optimal trapped field if proper pulse amplitudes and widths are applied. The effects of the amplitude, width, ramp rate, and shape of the pulsed current are reported. Transient responses of the HTS to pulsed magnetic fields are discussed and analyzed.

I. INTRODUCTION

Superconductors have many potential applications because they have no resistance to the flow of electricity below a certain temperature. With the recent developments in fabrication and joining of large-scale high-critical temperature superconductors of $RBa_2Cu_3O_x$ (where $R=Y$ or rare earth) [1], it has become practical to use HTS as cryogenic permanent magnets or quasi-permanent magnets due to their unique properties of strong flux pinning and great ability to trap high magnetic fields. Recent advancements in bulk processing made it possible for bulk RE-Ba-Cu-O superconductors to trap >4 T at 77 K and >17 T at 29 K [2]. Such high magnetic fields substantially exceed those produced by conventional permanent magnets, such as Nd-Fe-B, and are inspiring new applications both in the laboratory and in industry.

The maximum magnetic field that can be trapped by a bulk HTS monolith is determined by the critical current density J_c and physical size of the monolith. The conventional methods used to magnetize HTS are field-cooling (FC) magnetization and zero-field cooling (ZFC) magnetization. In FC magnetization, the HTS is cooled under a pre-established constant magnetic field. In ZFC magnetization, the HTS is first cooled down in zero

magnetic fields. Then, a constant external magnetic field is applied. A magnetic field will be trapped in the HTS after the applied field is removed. Based on Bean's critical state model, an external magnetic field equal to or greater than the maximum trapped field B^* is needed for FC magnetization. For ZFC magnetization, generally an applied field at least twice B^* is needed to trap a maximum field of B^* . With both FC and ZFC magnetization, a large constant external field is required to establish a trapped HTS field that approaches the saturation and steady-state conditions. Generally, this means that a large-scale superconducting solenoid magnet and associated bulky power supplies are needed. These requirements often restrict the use of HTS magnets for laboratory or industrial use.

Pulsed field magnetization (PFM) is an alternative way to magnetize HTS. In PFM, a pulsed magnetic field is applied to a pre-cooled HTS to trap a magnetic field. This method requires only a small and simple coil powered by a pulsed current to generate a suitable pulsed magnetic field. This system is more compact and may be advantageous for certain applications.

In a PFM system, the HTS is usually mounted inside a solenoid. A pulsed current through the solenoid coil generates a pulsed magnetic field that activates the HTS. With the goal of achieving the maximum trapped field and a symmetrical field distribution, PFM studies have reported effects of pulse amplitude, pulse width, pulse repetition rate, and varying sequential pulse shapes and amplitudes [3]-[8]. The optimization of the pulsed current profile proposed in this paper is carried out to generate, *in-situ*, the maximum (saturated) trapped magnetic field in a standard monolith at 77 K using an optimal compact magnetizing system.

II. EXPERIMENTAL DETAILS

An $YBa_2Cu_3O_7$ (YBCO) HTS disk (28 mm diameter x 10 mm length) made at Argonne National Laboratory with top-seed melt-texture technology is used for the trapped field experiments using the PFM method.

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The test arrangement, as shown in Fig. 1, consists of an HTS disk mounted near the top of a solenoid (OD, 53 mm, ID, 30 mm, length, 54 mm), which is made from 350 turns of AWG 16 copper wire. The solenoid, in series with a shunt resistor (50 mV/100 A), was connected to a pulsed current generator. The pulsed current was measured by sampling the voltage drop across the shunt resistor. The external magnetic flux density B_p at the center of the HTS top surface was calculated by multiplying the current by the coil constant (38.2 mT/A).

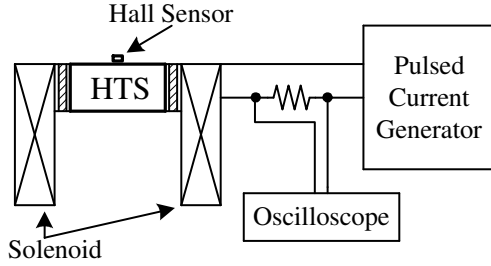


Figure 1. Schematic diagram of test apparatus.

During all the tests, the HTS and solenoid were submerged in liquid nitrogen (77 K). A Hall probe and a Gaussmeter (manufactured by F.W. Bell) were used to measure the vertical (C-axis) trapped magnetic flux density B_M (three minutes after each PFM) at the center of the sample's top surface. Also, the Hall probe was scanned over a plane about 0.5 mm above the top surface of the HTS disk to record the static distribution of trapped magnetic field. It should be noted here that the maximal trapped field measured by the Hall scan is somewhat less than that of the measured B_M because the scan plane was set about 0.5 mm above the HTS top surface.

III. RESULTS AND DISCUSSION

Several tests were performed to optimize pulsed current parameters. The results are discussed below.

A. Preliminary experiment

For comparison, this HTS was originally checked by FC magnetization.

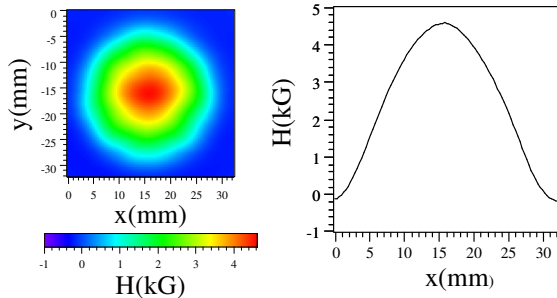


Figure 2. Trapped field profiles of FC magnetization.

The HTS disk is cooled to 77 K in a pre-applied uniform magnetic field of 0.6 T, and then the external magnetic field is slowly removed. The picture on the left

of Fig. 2 shows the trapped magnetic field profile, and the right curve is the magnetic field scan parallel to the x-axis through the center of the sample.

B. Pulsed current peak value

The peak value of the pulsed current obviously plays a dominant role in PFM. As the applied (pulsed) field increases, a very high circulating current is induced at the sample periphery. This induced shielding current inhibits the applied field from moving to the center of the monolith [8]. This is particularly important for short duration pulses. Empirically, it has been found that the external field generated at the maximum pulse current should be about 3 to 4 times the magnitude of the trapped field to obtain saturation. If the peak value of the applied field is too small, the field at the sample center will never reach the desired (saturation) value. If the peak value of the pulse current is too large, the sample will experience excessive heating from flux motion or from temporary transformation to normal state behavior, which will also reduce the trapped field.

Figure 3 shows the trapped field profile obtained after a single applied field pulse with relatively low peak value B_p of 0.9 T, generated by a peak current of 240 A (the pulse duration is about 50 ms). The shielding current generated during the pulse risetime limits the magnitude of the field at the sample center. After the decay of the applied field, the magnetic field inside the superconductor becomes trapped to produce the field profile shown in Fig. 3. The maximal trapped field is only 0.16 T (using an applied field with a peak value of 0.9 T), which is much less than the peak value of 0.47 T trapped by the FC method with a constant applied field of 0.6 T. The center of the sample only trapped 0.07 T.

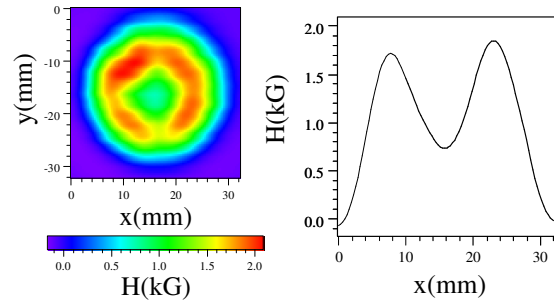


Figure 3. Trapped field profiles after PFM.
(Pulse: 240A peak/ 50 ms)

By sufficiently increasing the applied field peak value, field penetration through the HTS will increase, and the trapped field profile and peak value will become comparable to the saturation condition shown in Fig. 2 obtained by the FC method. A further increase of the applied peak value will not increase the trapped field since the circulating current is at the critical value.

Experimental results [3-4] and modeling simulation studies [5-6] show that, when the applied field is too high, the trapped field will be less than the saturation value. Heat generation resulting from flux motion increases the

temperature and weakens the flux pinning, lowering the saturation field. Clearly, there is a close interplay between sample heating resulting from the shape and amplitude of the charging pulse, and sample cooling (thermal conductivity, use of cooling channels, circulating liquid, etc.)

In our experiments, we found that the optimum applied field was obtained with a peak current of 480 A (pulse width of 50 ms), which generates a peak applied magnetic field B_p of 1.83 T. This produces a saturation field of 0.58 T in the monolith. Figure 4 shows the trapped field B_M as a function of different peak values of the applied field B_p .

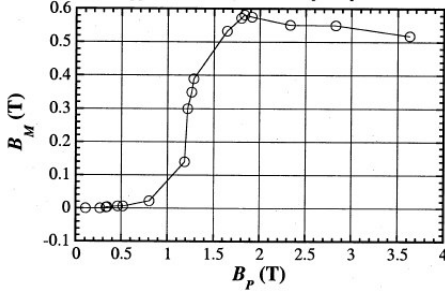


Figure 4. Maximal trapped field versus applied field (single pulse with width of 50 ms).

C. Pulsed current ramp rate and width

During the PFM transient, magnetic diffusion is important because there is not enough time to allow the magnetic field in HTS to reach steady state [7].

Under the magnetoquasistatic assumption, Maxwell's equations can be reduced to a magnetic diffusion equation,

$$D_m \nabla^2 B = \partial B / \partial t \quad (1)$$

where the magnetic diffusion coefficient D_m is

$$D_m = \rho(J) / \mu_0 \quad (2)$$

The characteristic time of magnetic diffusion is approximately defined as [7]

$$\tau = a^2 / D_m \quad (3)$$

In these equations, μ_0 is the permeability of free space, and a is the penetration distance, a characteristic field penetration distance into a superconducting medium. Also, the resistivity $\rho(J)$ is defined by

$$\rho(J) = E_C / (J / J_C)^n / J \quad (4)$$

where J_C is the critical current, E_C is the electric field strength at J_C , and n is an exponent much greater than 1, which depends on the superconductor's pinning strength.

Equation (4) indicates that the resistivity is a function of current density. In the superconducting state, $J = J_C$, and Eq. (4) reduces to

$$\rho(J_C) = E_C / J_C \quad (5)$$

Assuming that $J_C = 3300 \text{ A/cm}^2$ at 77 K and E_C is $1 \mu\text{V/cm}$, the calculated resistivity is $3 \times 10^{-9} \Omega\text{-cm}$. The value of a is 14 mm, which is equal to the radius of the sample. For these conditions, the characteristic time is

about a second; i.e., the time for the field to move from the outside of the sample to the center.

Based on Eqs. (2) and (4), the resistivity ρ and diffusion coefficient D_m increase dramatically with increasing current. That will dramatically decrease τ and, hence, speed the magnetic field penetration into the HTS. If a quasi-sine wave current pulse is applied to the solenoid, for a given pulse current peak value, a shorter duration pulse will have a higher dB/dt, which will induce a higher current and faster penetration in the HTS than a pulse of the same amplitude but longer duration. A low dB/dt pulse causes a lower induced current in the HTS and decreases the penetration speed, but the long pulse width will compensate the low penetration speed.

In our experiments, the pulsed current width was varied between 20 and 50 ms (480 A peak) to activate the sample. For these pulse widths, the deviations in the observed trapped fields were very small. The penetration time was small compared to the pulse risetime. It also was reported in [4] that 3 ms pulses result in slightly lower magnetizations compared with ten-fold longer pulses, and the difference was attributed to heat generation and geometrical effects.

In practice, it is desirable to avoid very short pulses with high peak value (high di/dt). Also very long pulses are not recommended because of high losses in the coil. Proper determination can significantly simplify design and cost of the magnetic system. It is also desirable to optimize the number of turns in the solenoid so that the peak charging current can be minimized while maintaining an acceptable upper limit to the voltage output from the current generator.

D. Pulse current shape

In modeling simulation studies, S. Bræck et al. [5] showed that it could be advantageous to use a charging current pulse with a risetime that is faster than the decay time. In their simulation, they considered a fixed peak current value and a constant magnetization time, 8 ms. The two cases studied were (1) the extreme case of an instantaneous field increase and a descent lasting 8 ms, and (2) a symmetric 8 ms pulse with 4 ms rise and 4 ms decay. Case (1) showed 8% more trapped flux because the heat dissipated in the beginning of the PFM has more time to flow out of the sample.

We conducted similar experiments using both 20 ms and 50 ms pulses with 1:1 and 3:1 falltime/risetime ratios (480 A peak). No obvious differences in trapped field were detected. We believe that any benefit from the variable ramp can be overcome by using an appropriate pulse width and multiple pulses strategies, since neither high di/dt nor a very short pulse is desirable for maintaining simplicity of the magnetic system design.

E. Multiple pulse strategies

Because of the complex interplay of phenomena involved in PFM, The trapped saturation field (maximal

trapped field) cannot readily be achieved with a single pulse. Also, inhomogeneities in J_C , present in all bulk HTS materials, apparently enhance the asymmetry in the trapped flux profile if only a single pulse is applied.

1) Repeat pulses

Trapped fields were measured after identical pulses were repeatedly applied to the charging coil. The quasi-sine pulse width was 50 ms, and the peak current varied from 400 A to 600 A. We found that 5-10% additional trapped field was usually gained with the second pulse, but no further significant changes were observed after additional pulses.

2) IMRA method

The Iteratively Magnetizing pulsed field operation with Reducing Amplitudes, abbreviated as IMRA, is very effective in magnetizing HTS (i.e., to achieve saturation by use of pulses with sequentially reduced peak fields) [4].

If proper peak values and widths are selected, saturation fields can be achieved by a three-pulse sequence. In our tests, the peak field of the initial pulse was about 4 times the saturation field with high ramp rate (20 ms width). This pulse provides a magnetic field sufficiently large to permit field penetration to the center of the monolith. The peak field of the second pulse was about 3 times the saturation field with reduced ramp rate (50 ms width). The second pulse increased the peak trapped field B_M by 8% and the field asymmetry was also reduced.

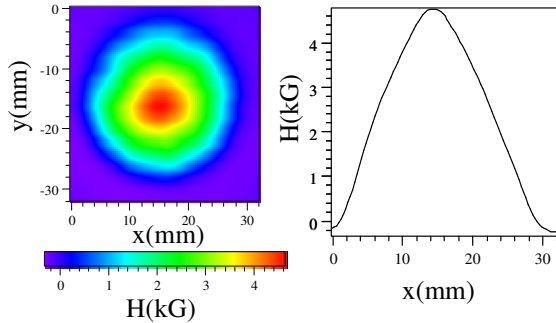


Figure 5. Trapped field profiles after PFM (three pulses with 600 A/20 ms, 500 A/50 ms, and 120 A/50 ms).

Finally, we applied a pulse with relatively small peak value (about equal to the saturation field) with low ramp rate (50 ms width). We found that the flux that escaped from the sample periphery during the previous operations was restored. The field distributions observed after the three-pulse sequence are shown in Fig. 5, which is compatible with the results in Fig. 2 obtained by the FC method on the same sample.

IV. SUMMARY

Compared to traditional FC and ZFC magnetization methods, PFM was shown to be a promising and practical

way to magnetize HTS monoliths, *in-situ*. It was demonstrated that the peak value of the current pulse plays a dominant role in PFM because of the strong shielding capability of HTS. The pulse width generally has little effect on the trapped field due to the interplay of penetration speed and pulse width. A very short or aperiodic pulse is not recommended in applications.

A single pulse usually cannot achieve a saturated trapped field in HTS monoliths. Also, the optimum condition cannot be achieved by simply repeating the same pulse. A sequence of pulses with gradually decreasing amplitude is more effective in obtaining saturation and the best field profile. A series of three pulses was enough to magnetize an HTS monolith with maximal trapped field if proper pulse amplitudes and widths were applied. The experimental results reported here were at 77 K. Larger fields can be trapped at lower temperatures. Experiments below 77 K are planned, and results will be reported in the future.

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